Races and Deadlocks

COMS W4118

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References: Operating Systems Concepts (9e), Linux Kernel Development, previous W4118s

Goals

- Identify patterns of concurrency errors
  - so you can avoid them in your code
- Learn techniques to detect concurrency errors
  - so you can apply these techniques to your code

Concurrency error classification

- Deadlock: a situation wherein two or more processes are never able to proceed because each is waiting for the others to do something
  - Key: circular wait
- Race condition: a timing dependent error involving shared state
  - Data race: concurrent accesses to a shared variable and at least one access is a write
  - Atomicity bugs: code does not enforce the atomicity programmers intended for a group of memory accesses
  - Order bugs: code does not enforce the order programmers intended for a group of memory accesses

Examples

- Deadlock

T1	T2
lock(m1);	
	lock(m2);
lock(m2);	
	lock(m1);

- Data race

T1	T2
++ balance	--balance

- Atomicity

T1	T2
	if (len > 200)
len = 100;	
buf = realloc(len);	
	memcpy(buf, str, 200);

- Order

T1	T2
p = NULL	
	*p;

Benign race examples

- Double-checking locking
  - Faster if v is often 0
  - Doesn’t work with compiler/hardware reordering

```
if(v) { // race
        lock(m);
        if(v)
                …;
        unlock(m);
}
```

- Statistical counter
  - ++ nrequests

Writing correct parallel code is hard!

- Too many schedules (exponential to program size), hard to reason about

- Correct parallel code does not compose → can't divide-and-conquer
  - Synchronization cross-cuts abstraction boundaries
  - Local correctness may not yield global correctness.

- We'll see a few error examples next

Example 1: good + bad → bad

- Result: race between deposit() and withdraw()

```
deposit() // properly synchronized
    lock();
    ++ balance;
    unlock();


withdraw() // no synchronization

    -- *balance;
```

Example 2: good + good → bad

- Compose single-account operations to operations on two accounts
  - deposit(), withdraw() and balance() are properly synchronized
  - sum() and transfer()? Race

```
void deposit(Account *acnt)
{
        lock(acnt->guard);
        ++ acnt->balance;
        unlock(acnt->guard);
}

int balance(Account *acnt)
{
        int b;
        lock(acnt->guard);
        b = acnt->balance;
        unlock(acnt->guard);
        return b;
}
```

```
void withdraw(Account *acnt)
{
        lock(acnt->guard);
        -- acnt->balance;
        unlock(acnt->guard);
}

int sum(Account *a1, Account *a2)
{
        return balance(a1) + balance(a2)
}
void transfer(Account *a1, Account *a2)
{
        withdraw(a1);
        deposit(a2);
}
```

Example 3: good + good → deadlock

- 2nd attempt: use locks in sum()
- One sum() call, correct
- Two concurrent sum() calls? Deadlock

```
int sum(Account *a1, Account *a2)
{
        int s;
        lock(a1->guard);
        lock(a2->guard);
        s = a1->balance;
        s += a2->balance;
        unlock(a2->guard);
        unlock(a1->guard);
        return s
}
```

T1:	T2:
sum(a1, a2)	sum(a2, a1)

Example 4: monitors don't compose as well

- Usually bad to hold lock (in this case Monitor lock) across abstraction boundary

```
Monitor M1 {
    cond_t cv;
    foo() {
        // releases monitor lock
        wait(cv);
    }
    bar() {
        signal(cv);
    }
};'
```

```
Monitor M2 {
    f1() {M1.foo();}
    f2() {M1.bar();}
};'
```

```
T1:          T2:
M2.f1();     M2.f2();
```

Outline

- Concurrency error patterns
- Concurrency error detection
  - Deadlock detection
  - Data race detection

Automatic software error detection

- Static analysis: inspect the code/binary without actually running it
  - E.g., gcc does some simple static analysis
    - $ gcc –Wall
- Dynamic analysis: actually run the software
  - E.g. valgrind
    - $ valgrind run-test
- Static v.s. dynamic
  - Static has better coverage, since compiler sees all code
  - Dynamic is more precise, since can see all values
- Which one to use for concurrency errors?
- Runtime detection
  - Detect problems when they happen in production
  - Cannot prevent only recover

A Historical Perspective on Deadlocks

- Deadlock handling is a problem once beloved of computer science theorists
  - Many deadlock avoidance/detection techniques in the literature
- Canonical Example
  - Dining Philosophers

Dining-Philosophers Problem

- Philosophers spend their lives thinking and eating
- Don't interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
  - Shared data: Rice (data set), lock chopstick [n]
- What happens if each one does Pick(left) before Pick(right)?

Deadlocks in Practice

- Ensure that the system will *never* deadlock
  - Easy to do by ordered locking, but programmers forget
  - Harder in the kernel – some code cant be preempted
- Allow the system to deadlock and then recover
  - Hard to do, recovery can be application specific
- In reality: ignore the problem and let applications deal with it; used by most operating systems, including UNIX
  - OS still cares about deadlocks within the kernel

Example from Android/Linux

From the kernel source tree: kernel/pid.c

```
/*
 * Note: disable interrupts while the pidmap_lock is held as an
 * interrupt might come in and do read_lock(&tasklist_lock).
 *
 * If we don't disable interrupts there is a nasty deadlock between
 * detach_pid()->free_pid() and another cpu that does
 * spin_lock(&pidmap_lock) followed by an interrupt routine that does
 * read_lock(&tasklist_lock);
 *
 * After we clean up the tasklist_lock and know there are no
 * irq handlers that take it we can leave the interrupts enabled.
 * For now it is easier to be safe than to prove it can't happen.
 */
```

Why do deadlocks occur?

Deadlocks can arise if the following 4 conditions hold at once:

- **Mutual exclusion:** only one process at a time can use a resource
- **Hold and wait:** a process holding at least one resource is waiting to acquire additional resources held by other processes
- **No preemption:** a resource can be released only voluntarily by the process holding it, after that process has completed its task
- **Circular wait:** there's a set {*A, B, C,* …, X} of waiting processes such that *A* is waiting for a resource held by B, B is waiting for a resource that is held by C, and X is waiting for a resource held by A

Here, resources can be anything, but in practice, usually locks

Dealing with Deadlocks

- Deadlock prevention
  - Always acquire locks in same order
    - Dining philosophers: first acquire left and then right? No!
    - Doesn't work when you can't sleep, e.g., Interrupt handler
    - Easy to do in userspace, need best practices
- Deadlock detection
  - Detect a deadlock after it has happened, and recover
- Deadlock avoidance
  - Basic idea: detect unsafe states that might dead to deadlock
  - Often need additional information about what processes will need what resources in the future

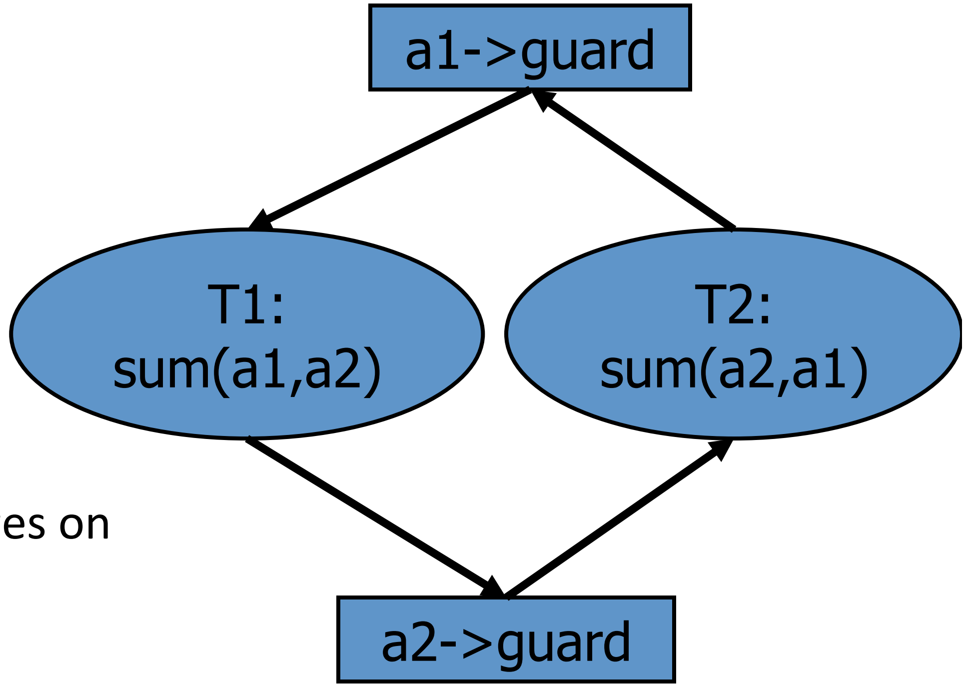
Deadlock detection

- Root cause of deadlock: circular wait
- Detecting deadlock manually: system halts
  - Can run debugger and see the wait cycle
- Detecting deadlock automatically: resource allocation graph
- Detecting potential deadlocks automatically: lock order

Resource allocation graph

- Nodes
  - Locks (resources)
  - Threads (processes)
- Edges
  - Assignment edge: lock->thread
    - Removed on unlock()
  - Request edge: thread->lock
    - Converted to assignment edges on lock() return
- Cycles ⇔ deadlock

- Problem: can we detect potential deadlocks before we run into them?



Resource allocation graph for example 3 deadlock

Detecting potential deadlocks

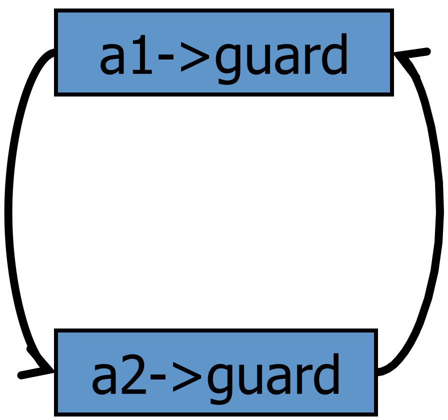
- Can deduce lock order: the order in which locks are acquired
  - For each lock acquired, order with locks held
  - Cycles in lock order ➔ potential deadlock

T1:

```
sum(a1, a2)      // locks held
lock(a1->guard) // {}
lock(a2->guard) // {a1->guard}
```

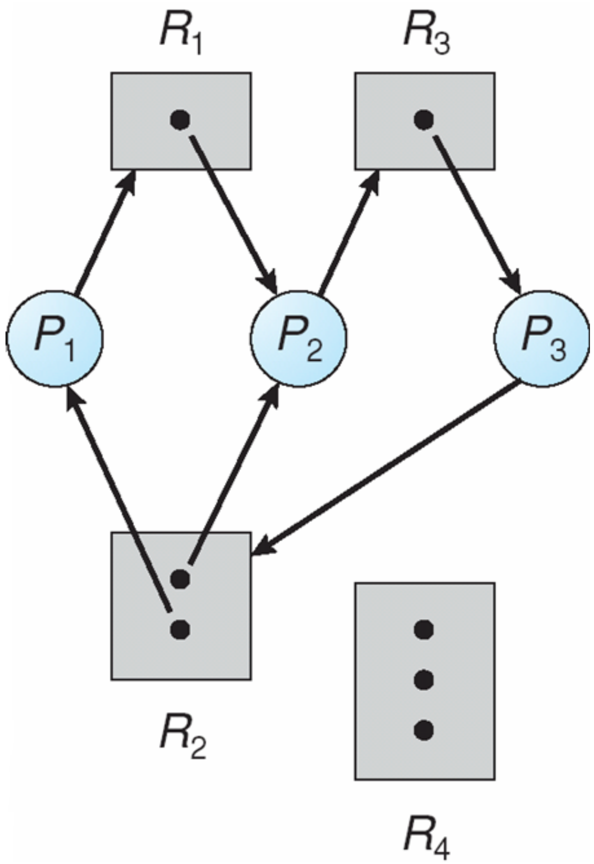
T2:

```
sum(a2, a1)      // locks held
lock(a2->guard)  // {}
lock(a1->guard) // {a2->guard}
```



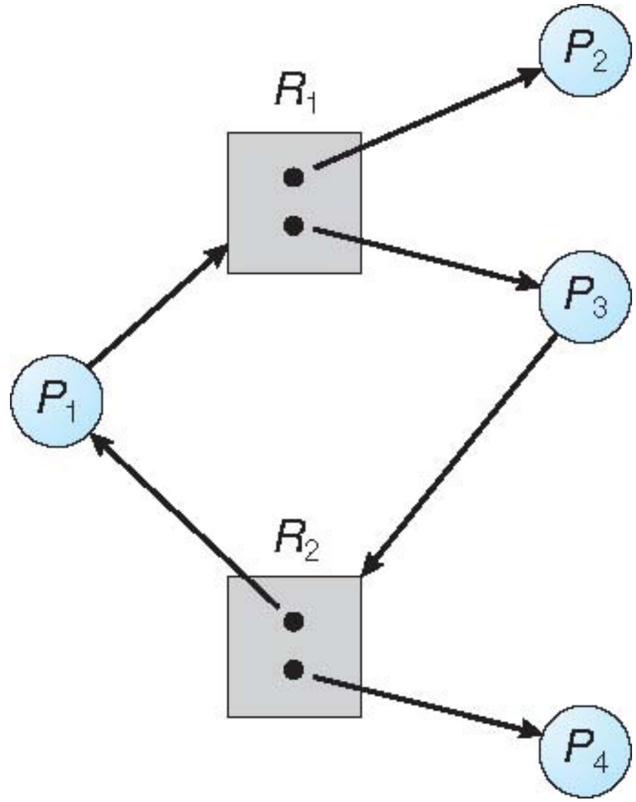
Cycle ➔ Potential deadlock!

Multi-Resource Resource Allocation Graphs



- Cycle and deadlock

Multi-Resource Resource Allocation Graphs



- Cycle but no deadlock

Basic Idea

- If graph contains no cycles $\Rightarrow$ no deadlock
- If graph contains a cycle $\Rightarrow$
  - if only one instance per resource type, then deadlock
  - if several instances per resource type, possibility of deadlock
  - Use Banker's algorithm and variants

Banker's Algorithm

- Designed by Dijkstra for THE multiprogramming system, 1968
- Multiple instances of resources
- Each process must a priori claim maximum use
- When a process gets all its resources it must return them in a finite amount of time
- Check if an allocation is safe and won't lead to a deadlock – i.e., there is some way to satisfy all future demands for resources

Safe States

- If a system is in safe state $\Rightarrow$ no deadlocks
- If a system is in unsafe state $\Rightarrow$ possibility of deadlock
- Avoidance $\Rightarrow$ ensure that a system will never enter an unsafe state.

Banker's Algorithm Variables

n: processes, and m: resource types

- **Available[m]**: how many resources of type m available
- **Max[n, m]**: total number of m type resources process n will eventually need
- **Allocation[n,m]**: how many m type resources n already has
- **Need[n,m]**: how many more m type resources does n needs
  - (Max[n,m] – Allocation[n,m]

Safety Algorithm

Basic idea: check if available resources are sufficient to satisfy all future demands for all processes in some order. I.e., we are in a safe state.

1. Let Work[m] be the hypothetical future availability for resource type m, and CanFinish[n] be true if process n can finish. Initial:

   Work = Available

   Finish[n] = false for all n

2. Find an i such that both:

   (a) CanFinish[i] = false

   (b) $Need_i \leq$ Work // needs fewer resources than available

   If no such i exists, go to step 4

3. Work = Work + Allocation[i] // i satisfied: will eventually release its resources
   Finish[i] = true
   go to step 2

4. If Finish [i] == true for all i, then the system is in a safe state

- Check if new allocation request will lead to safe state before granting
- Let Max=Request to detect if we are already in deadlock

Outline

- Concurrency error patterns
- Concurrency error detection
  - Deadlock detection
  - Data race detection

Race detection

- We will look at only data race detection
  - Techniques exist to detect atomicity and order bugs, but we won't discuss them in this class

- One approach to data race detection
  - Lockset algorithm
  - Eraser: A Dynamic Data Race Detector for Multithreaded Programs. In ACM Transactions on Computer Systems, 1997. http://dl.acm.org/citation.cfm?id=265927
  - Other techniques exist in literature

Happens-before definition

- Event A happens-before event B if
  - B follows A in the same thread
  - A in T1, and B in T2, and a synchronization event C such that
    - A happens in T1
    - C is after A in T1 and before B in T2
    - B in T2

Happens-before race detection

- Tools before eraser are based on happens-before
- Sketch
  - Monitor all data accesses and synch operations
  - Watch for
    - Access of v in thread T1
    - Access of v in thread T2
    - No synchronization operation between the accesses
    - One of the accesses is write

Problems with happens-before

- Problem I: expensive
  - Requires per thread
    - List of accesses to shared data
    - List of synch operations

```
T1:            T2:

++ y
lock(m)
unlock(m)
        -->  lock(m);
             unlock(m);
             ++ y;
```

- Problem II: false negatives
  - Happens-before looks for actual data races (moment in time when multiple threads access shared data w/o synchronization)
  - Ignores programmer intention; the synchronization op between accesses may happen to be there

Eraser: a different approach

- Idea: check invariants
  – Violations of invariants → likely data races
- Invariant: the locking discipline
  – Assume: accesses to shared variables are protected by locks
  – Every access is protected by at least one lock
  – Any access unprotected by a lock → an error
- Problem: how to find out what lock protects a variable?
  – Linkage between locks and variables undeclared

Lockset algorithm: infer the locks

- Intuition: it must be one of the locks held at the time of access

- C(v): a set of candidate locks for protecting v
- Initialize C(v) to the set of all locks
- On access to v by thread t, refine C(v)
  - C(v) = C(v) ^ locks_held(t)
  - If C(v) = {}, report error

- Sounds good! But …

Implementing eraser

- Binary tool
  - Pros: does not require source
  - Cons: lose source semantics
    - Track memory access at word granularity
- How to monitor memory access?
  - Binary instrumentation
- How to track lockset efficiently?
  - A shadow word for each memory word
  - Each shadow word stores a lockset index
  - A table maps lockset index to a set of locks
  - Assumption: not many distinct locksets

Problems w/ simple lockset algorithm

- Initialization
  - When shared data is first created and initialized
- Read-shared data
  - Shared data is only read (once initialized)
- Read/write lock
  - We've seen it last class
  - Locks can be held in either write mode or read mode

Initialization

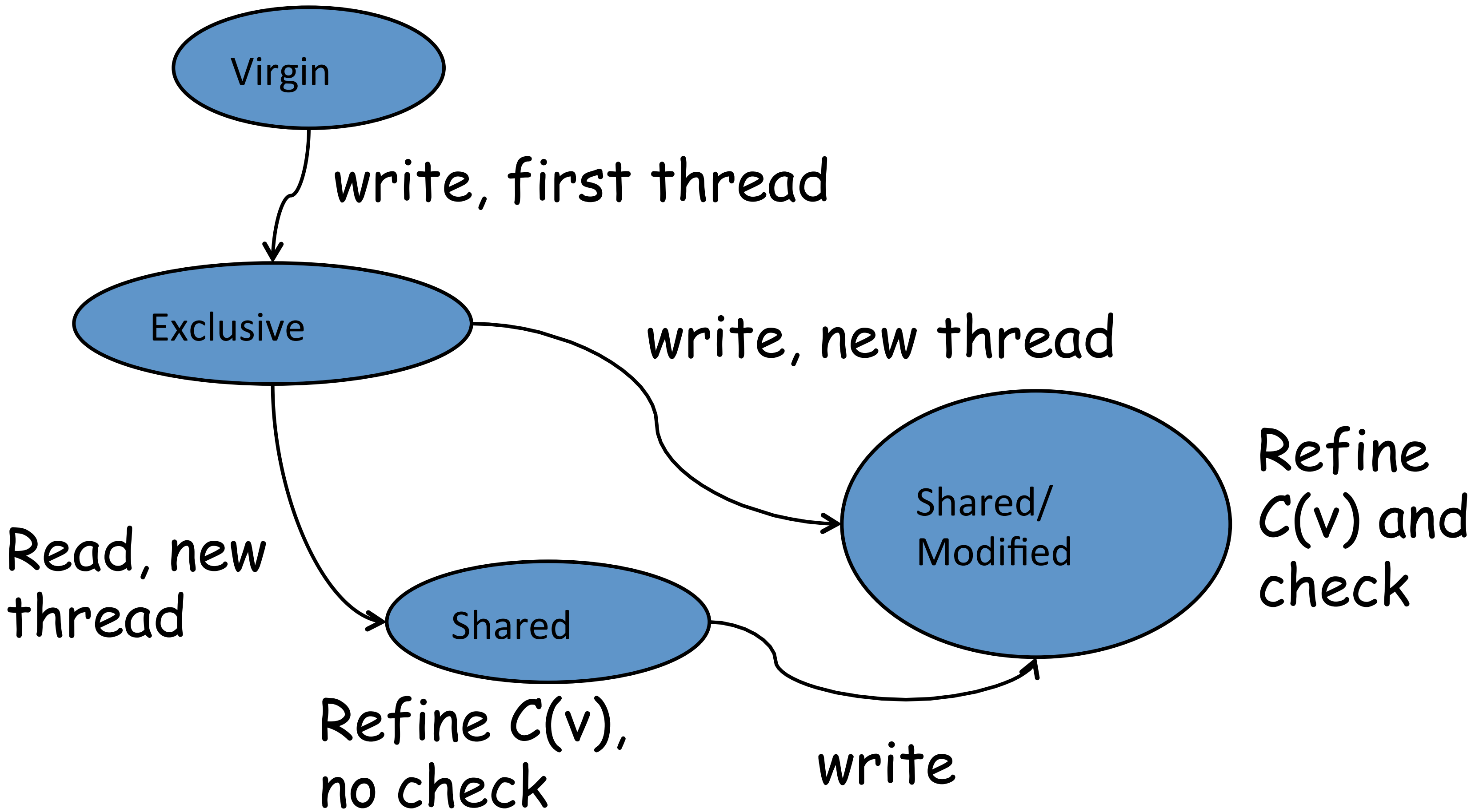
- When shared data first created, only one thread can see it ➔ locking unnecessary with only one thread
- Solution: do not refine $C(v)$ until the creator thread finishes initialization and makes the shared data accessible by other threads
- How do we know when initialization is done?
  – We don't …
  – Approximate with when a second thread accesses the shared data

Read-shared data

- Some data is only read (once initialized) ➔ locking unnecessary with read-only data
- Solution: refine C(v), but don't report warnings
  - Question: why refine C(v) in case of read?
  - To catch the case when
    - C(v) is {} for shared read
    - A thread writes to v

State transitions

- Each shared data value (memory location) is in one of the four states



Read-write locks

- Read-write locks allow a single writer and multiple readers

- Locks can be held in read mode and write mode
  - read_lock(m); read v; read_unlock(m)
  - write_lock(m); write v; write_unlock(m)

- Locking discipline
  - Lock can be held in some mode (read or write) for read access
  - Lock must be held in write mode for write access
    - A write access with lock held in read mode → error

Handling read-write locks

- Idea: distinguish read and write access when refining lockset
- On each read of v by thread t (same as before)
  - C(v) = C(v) ^ locks_held(t)
  - If C(v) = {}, report error
- On each write of v by thread t
  - C(v) = C(v) ^ write_locks_held(t)
  - If C(v) = {}, report error

Results

- Eraser works
  - Find bugs in mature software
  - Though many limitations
    - Major: benign races (intended races)
- However, slow
  - Monitoring each memory access: costly, 10-30X slowdown
  - Can be made faster
    - With static analysis
    - Smarter instrumentation (e.g., sampling)
- Lockset algorithm is influential, used by many tools
  - E.g. Helgrind (a race detection tool in Valgrind) http://valgrind.org/docs/manual/hg-manual.html